Lucinda Berthoud & Jonathan Walsh (2020) Using visualisations to develop skills in astrodynamics, European Journal of Engineering Education, DOI: 10.1080/03043797.2020.1742664

Using visualizations to develop skills in astrodynamics

Lucinda Berthoud
Aerospace Engineering, University of Bristol
Queen's Building, University Walk, Bristol, BS8 1TR, UK
lucy.berthoud@bristol.ac.uk

Jonathan Walsh
Aerospace Engineering, University of Bristol
Queen's Building, University Walk, Bristol, BS8 1TR, UK

ABSTRACT

Learning about the geometry and kinematics of bodies and their trajectories through space (or 'astrodynamics') is challenging due to its three-dimensional nature. To address this, the University of Bristol have developed simulation exercises for students based on a constructivist learning approach and variation learning theory. These exercises use orbit modelling software GMAT to develop skills and address misconceptions. The skills and misconceptions were drawn from the literature and suggested by students. Students were tested with a questionnaire both before and after performing the exercises. A survey at the end of the course provided feedback, which is discussed, along with proposals for further work. Overall, the study shows that 3D visualization exercises may offer an interesting way to improve conceptual understanding of certain aspects of astrodynamics, particularly for those students struggling with the subject matter.

Keywords: astrodynamics, variation theory, misconceptions, orbit modelling, 3D visualization, GMAT.

INTRODUCTION

To understand the movement of spacecraft and the paths that they take around planets, students studying physics and aerospace engineering learn about the geometry and kinematics of bodies and their trajectories through space. This area is called 'celestial mechanics' or 'astrodynamics' or, sometimes, 'mission analysis' and it is one of the most challenging parts of such a course, due to the 3D nature of the learning. These concepts are vital to the planning of space missions. They could be described as a threshold concept or "troublesome knowledge", as defined by Meyer and Land [1] . These authors have characterised such concepts as akin to a portal opening up a new and previously inaccessible way of thinking about something. There are many excellent texts in astrodynamics to provide a strong theoretical grounding [2–4]. However, 2D diagrams and verbal descriptions cannot fully describe the 3D motion of bodies through space. In exams and tests before this work commenced, students at the University of Bristol regularly showed evidence of misunderstanding and a failure to engage with astrodynamics. It was thought, therefore, to be an area suited to the application of 3D visualization and simulation tools. Previous authors have used computer simulations to teach engineering over a wide range of courses [5,6], some as virtual laboratories [7,8], but most as calculation tools. Certain studies have used commercial simulation tools in courses [9] and others have even used real-time simulation tools [10]. Others have used simulation tools to aid assessment [11]. Interestingly, there is evidence from previous studies that simulation-based learning can potentially enhance motivation as well as enhancing understanding [12]. Previous work has shown that "user ability to handle technology in order to move around between different representations of mathematical or physical objects promotes conceptual growth" [13]. Whilst simulations can enrich students' experiences, it important to remember that they cannot *replace* real world experiences. However, real world experiences of flying through space are currently hard to come by.

Fortunately, for astrodynamics, there are now several tools available in which to build models and permit the visualization of spacecraft astrodynamics. These include the NASA tool 'General Mission Analysis Tool' (GMAT), AGI's 'Systems Tool Kit' (STK), 'Orekit', 'Freeflyer' and even the physics-based game 'Kerbal Space Program'. These are based on numerical solution of the equations of motion and enable users to manipulate the views of the path of the spacecraft.

Previous authors have already looked at a number of specific examples of the use of these tools, including orbital elements, geostationary eclipse season, launch windows, reference frames, lighting, attitude, formation flying and manoeuvres [14,15]. Others have used them to reinforce satellite communications engineering concepts [16]. In other work, it has been maintained that the introduction of these tools at the expense of student exposure to the analytical basics of astrodynamics may lead to a reliance on simulation, instead of analysis, to solve problems [17].

The 'constructivist' view of learning posits that learning is not just an acquisition of information, but that learners construct their knowledge by building on what they already know [18]. Knowledge is actively constructed by the learner and not passively received from the outside [19,20]. Learners come to the learning situation with their own ideas. Some of these ideas are "ad hoc and unstable; others are more deeply rooted and well developed". The ideas are often at odds with accepted scientific ideas, and some of them may be persistent and hard to change.

Research studies have demonstrated that student "conceptions" can be resistant to traditional instruction. Despite passing examinations, students can still hold incorrect ideas about a topic. Incorrect ideas or 'misconceptions' have been much discussed in previous work [21]. Previous authors have proposed principles for effective simulation-based learning [22]. These include familiarity with the software package used, the possibility to demonstrate problem solving skills, sufficient time, the complexity of the task should approach reality, encouragement of peer interaction, the provision of thorough instructions, transferable knowledge and an open-ended task [23–25].

To learn something, the learner must discern what is to be learned (the object of learning), and to achieve this the learner must experience potential alternatives. The pedagogical design of the simulations can therefore be underpinned by variation theory which arises from phenomenography [26,27]. So, if the learner encounters systematic variation against a background of invariance, it can contribute to the teaching and learning of disciplinary concepts. According to this, learning is enhanced when a critical aspect of a phenomenon is varied, while all other aspects are kept constant. The implication of this, is that any simulation should try to encourage variation of a critical aspect of a phenomenon, while keeping other aspects constant or invariant [28]. For example, in previous work in Fluid Mechanics, a common disciplinary concept that students experienced particular difficulty in learning was identified, then the variations in student understanding of that concept were investigated and pedagogical interventions informed by the principles of variation theory were designed [29]. Therefore, in this work, the aim was to improve student learning in astrodynamics through simulations which address specific misconceptions and which develop specific skills. It is proposed here that students need to 'experience' the astrodynamics for themselves in order to construct meaningful knowledge - by adjusting/building on existing mental models, free from misconceptions.

In section 1, definitions of the astrodynamics terms used are provided, the content and structure of the astrodynamics course is described, and a brief description of the basic knowledge assumed by the course and the research problem is summarised. Section 2 provides an introduction to the methodology used for the research, a description of how the learning objectives are derived from the skills and misconceptions targeted for the simulation and the choice of the astrodynamics tool. In section 3, the development of the exercises is presented. Section 4 covers the evaluation of the research with results from the pre- and post-tests and student feedback on the simulations. In section 5, the results and limitations of this work are discussed. Section 6 proposes further work and the conclusions follow in section 7.

1 BACKGROUND

1.1 Definitions

Through this work, some technical terms from astrodynamics are used, these are defined here in an alphabetical list for those interested:

Apoapsis – the farthest approach of a satellite to a target body [30]
Delta V – the change in speed required to move from one location to another in space
Geostationary orbits – a satellite remaining always above the same point on the Earth's equator [3]
Ground tracks – "ground tracks" are the projection of the satellite's orbit onto the surface of the planet it is orbiting [3]
Hohmann transfers - A Hohmann transfer is the most efficient way, in terms of fuel, to change the altitude of a circular orbit [3].
Inclination – the angle between the orbital plane and the equatorial plane, measured according to the right-hand rule [3].
Molniya orbits – the Molniya telecommunications satellites are in 63degree inclination orbits having a period of 12 hours which are notable for having long linger times over higher latitudes and are therefore a useful alternative to Geostationary orbits [3]
Orbital elements - six independent parameters that define the position and velocity of a body at a given time or as a function of time [31]
Prograde burns – forward burns which increase the velocity in the direction of flight
Retrograde burns – reverse thrust burns in the opposite direction to the direction of flight
Rendezvous manoeuvres - the bringing together of two spacecraft in orbit at a planned location and time [30].
Sun-synchronous orbits – those whose orbital plane makes a constant angle with the radial from the Sun to the target planet [3]

1.2 Content of Astrodynamics of Space Systems course

The University of Bristol has delivered a Space Systems course module as part of the 4-year Aerospace Engineering 'Integrated Masters' degree (Bachelor and Master's rolled in to one course) for many years. It is a compulsory course unit in the second year of Aerospace

Engineering and is optional for students from the Engineering Design course. The cohort studied was 148 students. It is worth 10 credits out of 120 credits for the year and originally comprised of 24 hours of lectures with 3 examples sheets. Of the 24 hrs of lectures, 7 hours are used to cover a theoretical introduction to orbits, which is of particular interest here. This includes: Kepler's and Newton's laws (and proving Kepler's laws from Newton); conic sections; 3D reference systems; orbital elements; ground tracks and different types of orbits; 2-body motion; The Kepler equation and the vis-viva equation; out-of-plane manoeuvres; Hohmann transfers; basic rendezvous principles. The other lectures cover various aspects of spacecraft design such as power, propulsion, attitude and orbit control etc.

1.3 Establishing the basics

A Space Systems course is based upon foundations built in physics courses at primary and secondary school level. Understanding of astrodynamics depends on an accurate understanding of the concepts of night, day, seasons, gravity, orbiting and rotation. According to Sadler [32], there are many astronomical misconceptions through school including that the Earth's orbit around the Sun is highly elliptical, that the reach of humans into space is far greater than in reality, that orbits are not a result of gravity (because of a belief that there is no gravity in space), that orbital and rotational periods are only an Earth day for all objects etc. Going from the constructivist model that learning is built upon previous layers of learning, it is important to test these basic principles and so a formatively assessed quiz with polling is given in the first lecture. The scores are usually 90-100% with students showing an excellent proficiency in the basics. It should be noted that the University of Bristol is a highly selective University that chooses students based on their grades at the end of secondary education.

1.4 The problem

In the Space Systems course, which is the subject of this research, the theoretical background of introductory astrodynamics is presented in standard lecture format. Despite an excellent grasp of the basic principles, students regularly showed evidence of misunderstandings and a failure to engage with astrodynamics material in end of year exams and coursework. Many students avoided optional astrodynamics questions in exams and exhibited gaps in understanding. The authors were mindful that one of the possible explanations for low student performance is that teachers may "overestimate students' ability to learn a concept, and thus not realize that they need to spend more time teaching a particular concept"[33]. So, the aim was to try adding in some more opportunities for students to master this subject matter using simulations.

Therefore, the research question here is to whether it is possible to use 3D visualization exercises to help students to improve their skills and to address certain misconceptions in astrodynamics.

2 METHODOLOGY

2.1 Introduction

The methodology used in the research is illustrated in Figure 1. The many excellent literature texts in the subject of astrodynamics provides the background to the theoretical foundation for the course. This forms the core content of the course and contributes towards the list of skills to be addressed in this work. Also contributing to the choice of skills are the list of misconceptions. These misconceptions come from a review of the exams and coursework and topics nominated by students that they find 'tricky'. Together the skills and misconceptions drive the learning objectives for the simulations. These learning objectives drive the requirements for the selection of the simulation tool, together with other factors such as cost. A review of the tools provided some possibilities from which the tool was selected. Then the exercises were devised. The exercises were piloted on a small group of students to gather feedback to improve them. After the exercises were developed a test was developed to test whether the students had improved skills and misconceptions.

Figure 1

The experience of the process for students is illustrated in Figure 2. Pre- and post-testing was set up to compare the student's misconceptions and skills before (Test 1) and after (Test 2) the simulation. Test 1 took place after the lecture course was finished but before the simulation exercises. Then the students undertook the simulation exercises and a few days later took Test 2. Test 2 contained the same questions as Test 1, but in a different order. A survey of the cohort was carried out at the end of the course.

Figure 2

2.2 Addressing skills and misconceptions

There are a set of skills expected of those wishing to be versed in astrodynamics. These are covered in most standard astrodynamics textbooks [2–4]. An introduction for those spending a few hours on the topic, such as our students, might include the skills listed in Table 1.

As a formative assessment exercise, students were asked which topics they found 'tricky'. They were then asked to spend some time researching this topic and were given feedback on their explanations to correct their understanding (if necessary) by the authors. The top topic areas selected by students are listed in Table 2.

Table 1. Basic skills required in introductory astrodynamics

No.	Skill
1	Varying orbital elements and observing the effects
2	Interpreting ground tracks
3	Exploring features of Sun-synchronous, Molniya and Geostationary orbits
4	Adding pro and retrograde burns and seeing the effects
5	Performing inclination changes
6	Performing Hohmann transfers
7	Understanding frames of reference

Table 2. Top 'tricky topics' selected by students

No.	Tricky Topic
1	Hohmann transfer
2	Inclination change
3	Rendezvous

4	Escape velocity
5	Orbit velocity calculations
6	True anomaly calculations
7	Orbital elements

A review of previous exam papers and the feedback given in the formative assessment of topics listed in Table 2 was conducted in order to discover where misconceptions in this topic lie. Some of the main misconceptions have been listed in Table 3. The next task was to use all of this information to design the simulations.

Table 3. Examples of common misconceptions in introductory astrodynamics

No.	Misconception
1	Confusing the orbital elements
2	Thinking that satellites move faster in their orbits with increasing altitude
3	Thinking that Geostationary satellites are not moving (relative to stars)
4	Forgetting that Earth rotates when considering ground tracks
5	Thinking that a Hohmann transfer is composed of one burn only
6	Thinking that for a chaser spacecraft to catch up with a target in orbit in a rendezvous, it must accelerate in the same orbit.

2.3 Objectives for the Simulations

An intersection of the topics in Tables 1, 2 and 3 gave the material selected for the simulations: frames of reference, orbital elements, ground tracks, Hohmann transfers, inclination changes and rendezvous. Of the challenging topics, it was not possible to integrate No. 4 – ‘Escape velocity’ and No. 6 – ‘True anomaly calculations’ into the simulations as they were harder to integrate with the other topics, covering slightly different areas.

The pedagogical design of the simulations was underpinned by variation theory. This theory was applied to the design of the simulations, for example when each of the orbital elements was given in an exercise, only one parameter was varied at a time. Each objective was chosen to be a gradual step-by-step building up of the critical concepts necessary to the understanding of the topic. To allow this to happen, the learning objectives were formulated as below, to:

- *Explore the software interface*
- *Compare the differences between two orbital frames of reference*
- *Explore, one by one, the difference that each Keplerian element makes to an orbit*
- *Interpret the ground track for each of the above variations*
- *Explore several useful orbits such as Sun Synchronous, Geostationary and Molniya orbits*
- *See the process of rendezvous as a succession of burns to gain/lose altitude to match orbits*
- *Perform an orbital plane change by varying the inclination of the orbit*
- *Perform a Hohmann transfer by varying the altitude of the orbit through burns*
- *Explore an inclination change combined with a Hohmann transfer*

2.4 Choice of Tool

There are now a wide variety of tools available for performing mission analysis and astrodynamics. The University of Bristol started out in 2011 using Systems Tool Kit (STK) by AGI. When the STK provider in Europe started charging for licences, another tool was required. The criteria for selection included: scientific credibility, ability to perform Low Earth Orbit, interplanetary, low energy and constellation missions, user support, documentation and a low licence fee. Based on these criteria, a free tool developed by NASA Goddard Space Flight Center: 'General Mission Analysis Tool' (GMAT) was selected [34]. It has been extensively tested and verified and has been used for more than 9 NASA missions [35]. The system can display trajectories in space, plot parameters against one another, and save parameters to files for later processing. The trajectory and plot capabilities are fully interactive, plotting data as a mission is run and allowing users to zoom into regions of interest. Trajectories and data can be viewed in any defined coordinate system, and GMAT allows users to rotate the view and set the focus to any object in the display [34]. According to its developers, GMAT is a space mission design software system for the design and optimization of missions anywhere in the solar system ranging from Low Earth Orbit to Lunar, Libration point, and deep space missions. It supports Windows, Mac and Linux platforms and has interfaces with MATLAB and Python. GMAT can be controlled via a Graphical User Interface, or from a scripting language based closely on MATLAB (which was useful as our students are familiar with MATLAB).

3 EXERCISES

3.1 Developing the exercises

The simulations were developed based on the principles put forward for the effective use of simulations in teaching engineering discussed in the introduction. The exercises were presented as a series of increasingly challenging problems for the students to solve. In the lectures, the students were told that the tools were for the benefit of practical learning about the theory presented. They were encouraged in the instructions to 'play and experiment' with the tool, in order to explore the physical phenomena. The students undertake these simulations during two sets of computer laboratory classes of 2 hours each, just after the theoretical lectures. For the first series of exercises, all students who started the laboratory at the beginning were finished by the end of the class. For the second series of exercises, which were more challenging, students were encouraged to carry on working in their own time if they did not finish, although many finished in the class. A demonstration script was provided at the beginning of each series of exercises for the students to gain an appreciation of the power of the tool, its use in real world situations and to demonstrate particular learning points. The first demonstration concerned satellites in different types of orbits. The second concerned a rendezvous between a Soyuz transport capsule and the International Space Station. In the exercises, the students were encouraged to ask each other questions and interact, although each was responsible for doing their own exercises. It has been the experience of the authors that if the students work in pairs, the less confident students will sit back and observe, rather than participating, so individual work was encouraged.

3.2 Instructions

A set of step-by-step instructions through the exercises and tool menus was developed by the authors. These instructions also include explanations of the different commands and interfaces. The students were also required to answer questions as they progressed through the exercises. It is worth noting that some excellent tutorials are provided by the GMAT developers, but they are aimed at allowing users to become familiar with the software itself, not at explaining or helping students to better understand astrodynamics theory. If the students do not complete the exercises during class time, they are asked to finish them in their own time. Although voluntary, these classes are attended at 90-95%. Staff and teaching assistants are available during the class to answer all questions. The worksheet questions are aimed at inspiring the student to explore and question what they see, e.g.: "*Sat01 has completed a complete orbit which starts and finishes at the periapsis, but there is a gap in the ground track. Why do you think this is*?" Figure 3 shows an example of the instructions. The following sections describe the exercises covered in the instructions and their rationale.

Figure 3

Orbital elements

This exercise addressed three things: the topic "Orbital Elements" which was selected as challenging for students; the skill "Varying orbital elements and observing the effects" and the misconception "Confusing the orbital elements". Textbooks on astrodynamics will usually list and define each of the 6 orbital elements (the Classical Orbital Elements: semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of periapsis and true anomaly are used here), with the aid of a labelled diagram. Understanding of the elements requires some 3D spatial imaging skills and without practice many students do not understand them fully after learning the theory in class. To help students to explore these elements, three satellites were modelled with identical orbital elements. Then one element, e.g.: inclination, was varied by the students for each of the three orbits so that they could simultaneously see three orbits with three different inclinations. This 3D visualization allowed them to see how different values for the elements affect their orbits. The ability to zoom, pan and view the orbit from different angles made it easier to see how the orientation of the orbit has changed. The students could compare and explore the different elements one by one.

Ground Tracks

This exercise addressed the skill "Interpreting ground tracks" and the misconception "Forgetting that Earth rotates when considering ground tracks". Ground tracks are presented as 2D plots on a map of the planet concerned. A simple inclined circular orbit gives a sinusoidal ground track. Ground tracks can take on unexpected forms, such as loops, but the cause of these forms becomes clearer when they can be matched with the 3D view of the spacecraft orbiting above the rotating body. At the beginning of the laboratory, a demonstration script showed three types of orbits with their matching ground tracks for the students to explore. The students were asked to compare the ground track with the orbit, to see how they link. They were then asked to work out the inclination of an orbit from the ground track plot only and then to compare it with the 3D orbit. Figure 4 shows the ground tracks for three different types of orbits using GMAT.

Figure 4

Special orbits

The selection of a satellite's orbit is driven by the mission it is required to perform, whether science, Earth observation or communications. A few orbits are particularly interesting for their features. They include Geostationary, Sun-synchronous and Molniya orbits. To address the skill "Exploring features of Sun-synchronous, Molniya and Geostationary orbits" and misconception "Thinking that Geostationary satellites are not moving (relative to stars)", the students were required to set these orbits up as simulations and were then asked to work out why they might be useful from their ground tracks and elements.

Pro and Retrograde burns and their effects

To develop the skill: “Adding pro and retrograde burns and seeing the effects” and building towards dealing with challenging topics “Hohmann transfer” and “Rendezvous” and associated misconception: “Thinking that for a chaser spacecraft to catch up with a target in orbit in a rendezvous, it must accelerate in the same orbit”, an exercise was devised for students to experiment with adding pro and retrograde burns to orbits. For rendezvous between a target spacecraft and a chaser spacecraft, if the target is travelling ahead of the chaser, then the chaser needs to drop into a lower orbit to allow it to catch up. In a demonstration simulation provided to the students, they can see how a chaser Soyuz performs two retrograde burns to drop into the lower altitude orbit and then two prograde burns to return to the target’s altitude. This is counterintuitive. Many students believe that performing a greater prograde burn (or ‘*flooring it*’, according to one student) would help the chaser spacecraft catch up to the target spacecraft, whereas it will just raise the apoapsis of the orbit. Many students are startled to see this effect in practice and need to see the evidence both in 3D and in a graph of velocity and time, such as in Figure 5, which can be generated live in front of them in the simulation.

Figure 5 here

Inclination manoeuvres

To address the skill “Performing inclination changes” and challenging topic “inclination changes”, students completed an exercise on these changes, which are burns at an angle to the direction of travel. First, they performed theoretical calculations to work out the value of the burn elements, then they set up the burn in the simulation. They then compared the results of their calculations to results given by the model.

Hohmann transfers

Hohmann transfers are the top topic named as difficult by students and they are covered by skill “Performing Hohmann transfers”. These transfers involve two burns; the first to raise the apoapsis to the altitude of the desired orbit, then the second to circularise the new orbit. Students frequently forget the second burn (misconception “Thinking that a Hohmann transfer is composed of one burn only”). By seeing the result of modelling without a second burn, the aim was for the students to realise the necessity of two burns. The students had to calculate the theoretical values of the two burns using standard theory and were then asked to compare their theoretical results with the model results and to explain any differences.

3.3 Developing the pre and post tests

In order to evaluate the effectiveness of the exercises, it was desirable to attempt to assess the impact of the simulations. Some multiple-choice questions to ask the students both before and after the simulations were developed. Each question was designed to cover a particular topic. A subset of astrodynamics concepts was selected for the tests due to time constraints. The test consisted of 8 multiple choice questions, the questions and answers are given in Appendix A. The first test was taken at the end of the last lecture on astrodynamics and just before the exercises. Test 2 was done the week after the students had done the exercises, at the end of a lecture period. There was a time period of 4 weeks between the tests. Overall, 37 students took both tests and form the population for comparison. The tests were not anonymous as the

comparison of the pre and post test results required identifying whose test was whose. The tests were used as formative assessment and this was made clear to the students. No preparation for either test was required.
Topics of the questions were:

1. Orbital element measurement
2. Orbital element listing
3. Kepler's laws and velocities of satellites at different orbital altitudes
4. Geostationary satellite visualization
5. Ground tracks rotating earth
6. Ground track inclination
7. Hohmann number of burns
8. Rendezvous

Both tests were carried out in class under test conditions (no conferring allowed). Answers were provided immediately after the tests, so that the students could learn immediately from any mistakes.

3.4 Student survey

A student evaluation survey was carried out at the end of the course. This was administered on paper in the last lecture of the course. The survey was anonymous and, judging by some of the comments, most of the students appeared to believe the comments were genuinely anonymous. 53 responses were collected out of a total of 148 students on the course. The small numbers were due to the survey being performed on the last lecture of the course when attendance is usually at its minimum.
The questions used in the survey are given below and the answers are discussed in the next section.

- *Rate each element of the course out of 10, including individual lecturers, the materials and the coursework*
- *How did the GMAT labs help you in your learning, if at all?*

4 EVALUATION

4.1 Test results

Test 1 and 2 were evaluated for the students who answered both sets of tests. There were 37 students who took both tests. For these, the overall average for Test 1 was 68% and the overall average for Test 2 was 83% (see Table 4). The relatively high average for Test 1 showed that before the simulations began, many students already had a good baseline grasp of the topics tested. The 13 students who scored less than 5 out of 8 improved their scores by an average of 37% - a significant improvement.

Table 4: Results for individual questions in tests 1 and 2.

Question	Topic	Test 1 result %	Test 2 result %
1	Orbital elements measurement	16	46
2	Orbital elements components	78	84
3	Velocities of satellites	53	72

4	Geostationary orbit	66	81
5	Ground tracks, rotating Earth	68	86
6	Ground track, inclination	89	100
7	Hohmann, number of burns	89	100
8	Rendezvous	81	97
Average		**68**	**83**

4.2 Feedback results

At the end of the unit, students were requested to complete an anonymous paper feedback questionnaire. In this they were asked: "*Rate each element of the course out of 10, including individual lecturers, the materials and the simulations*". From the 53 responses, 83% rated the coursework at 7 or more out of 10. The students were also asked "*How did the GMAT labs help you in your learning, if at all?*" The responses included many variations on: "*Helped me to understand concepts that were hard to visualise*". Three students emphasised the importance of playing with the topic matter to master it. But also, negative comments included: "*I didn't find them that helpful. There were no clear instructions for how to do a Hohmann transfer, this was left for you to work out, which was hard*". Two people suggested: "*Maybe a longer lab time slot would give more time to understand what you are doing and what the results show*". In general, the feedback questionnaire indicated that the students found the exercises helpful, although some students wished for more time in the class and some students found the final self-guided exercise difficult.

5 DISCUSSION

The aim of this work was to improve student learning in astrodynamics through simulations which address specific misconceptions and develop specific skills. From the comments in the feedback, the activity appears to enable the students to develop skills: "*They teach you how to do something and then get you to try yourself*" and apply principles that they have learned in class: "*They helped apply the theory*". Some students indicated that the simulations helped them to further their understanding of key concepts: "*They reinforced knowledge of orbits and more complex concepts*". The simulations also appeared to help them to learn how to structure their engagement with astrodynamics: "*I learned how to think and approach the problem*. In the simulations, the students 'experienced' the astrodynamics for themselves in order to construct meaningful knowledge: "*Completing the transfers and manoeuvres helped me understand the procedures*". They were doing this in the areas which they found 'troublesome' or which were susceptible to misconceptions: *"It helped me understand something difficult to imagine, such as rendezvous*". As the exercises were based on the evidence-backed idea of systematic variation against a background of invariance [29], they could contribute to an improved understanding of disciplinary concepts: "*They helped to visualise the effects of changing different orbital elements*".

It was apparent during the simulations that students were collaborating with each other in order to problem solve some of the exercises, whilst taking responsibility for their own work. This was not one of the learning outcomes, but it was highly desirable. Equally, it was clear that the students were experimenting with the software; they were speculating, testing ideas and learning from experience - all an essential part of active learning: "*It was quite fun and we all know that playing is the best way to learn*"! Giving them control over their learning enabled them to move at their own pace. The simulations offered the opportunity to try, fail and receive immediate feedback. However, they could also get help when they were struggling. One commented: "*It helped having staff to ask questions to*". Help in visualising orbits was mentioned by many students as being the main benefit of the simulations: "*Allows you to visualise orbits and all the methods of changing them*". Visualization is an important skill to develop in engineering and this activity has provided a way of mastering this skill which they find interesting and exciting: *"The simulations substantially increased my interest in Space Systems*". This chimes with previous research which has found that simulations can enhance motivation as well as increasing understanding [12].

One of the inputs to the design of the simulations was a list of topics that students had nominated as being difficult. It is useful to question the validity of the method of asking students to suggest themselves what they find difficult. It is, for instance, possible that some students selected a topic which they already understood in order to make the tasks easier or that they selected a topic which they found interesting, rather than difficult. The test setup was not ideally implemented from a research point of view. A setup with a control group would be better but not popular with students. Alternatively, two similar, but different, tests could have been used in order to reduce the effect of memorization among the students. The scores on the first test were higher than expected, so possibly the test was easier than planned. Given that the two tests were 4 weeks apart, it was to be expected that some settling of the information and skills would be expected. But 78% of the students improved their scores in Test 2. The improvements in scores could also be due to the students having spent some focussed time on these topics with the simulation exercises. Some students, particularly those who scored highly on Test 1, showed little improvement. It may be that these students did not need the exercises to aid their understanding. From the test results, lower scoring students appeared to benefit most from the simulations, but it is hoped that the other students gained much from the active learning aspects of the simulation exercises.

6 FUTURE WORK

The feedback from the students suggested reducing the scope of the exercises or increasing the length of the class, so an extra session will be provided in the next iteration of the exercises. This study has also drawn attention to the most troublesome knowledge within the course and so the authors plan to improve the clarity of the lecture part of course in these aspects. In the future, the authors are considering the possibility of "flipping the classroom" in order to move the entire course towards an active learning method [36]. This would involve extending the simulation exercises to cover more aspects of orbital mechanics (currently only the most challenging topics have been covered) and moving some of the lecture theory to either note or short video format. However, as discussed earlier, it is recommended to avoid replacing exposure to the analytical basics of astrodynamics entirely with simulation exercises [17].

7 CONCLUSIONS

This study has applied learning theory to the development of simulations for use in teaching astrodynamics – a topic challenging due to its 3D nature. A list of basic skills, 'troublesome knowledge' selected by students and common misconceptions were used to develop a series of simulation exercises using NASA orbit modelling tool GMAT. These included orbital elements, ground tracks, special orbits, Hohmann transfers, prograde, retrograde and inclination burns. Feedback gathered from a cohort of students from the University of BRISTOL revealed that the simulations offered students the opportunity to develop their skills and challenge their misconceptions. They were able to test ideas and to gain immediate feedback on their learning. The study confirmed that simulations can be used to improve visualization of 3D concepts and may enhance motivation for a challenging topic. This work gives an example of how using variation theory to structure an exercise can facilitate conceptual understanding. Pre- and post-tests indicated that simulations may particularly help students who are struggling with astrodynamics.

ACKNOWLEDGMENTS
One of the authors was supported by the UK Engineering and Physical Sciences Research Council iCASE grant no. 15220191 whilst preparing this work.

REFERENCES

[1] J.H.. Meyer, R. Land, Overcoming Barriers to Student Understanding: Threshold Concepts and Troublesome Knowledge, 1st ed., Routledge, Oxford, 2006.

[2] D. Vallado, Fundamentals of Astrodynamics and Applications, 2nd ed., Microcosm Press and KluwerAcademic Publishers, El Segundo, California, 2004. doi:10.2514/2.4291.

[3] H.D. Curtis, Orbital Mechanics for Engineering Students, 2nd ed., Elsevier Ltd, Oxford, 2014. doi:10.1016/B978-0-08-097747-8.00007-4.

[4] R.H. Battin, An Introduction to the Mathematics and Methods of Astrodynamics, AIAA, Reston, Virginia, 1999. doi:10.2514/4.861543.

[5] S. Montgometry, H.S. Fogler, Selecting Computer-Aided Instructional Software, Journal of Engineering Education. 85 (1996) 53–60. doi:10.1002/j.2168-9830.1996.tb00208.x.

[6] K.D. Dahm, R.P. Hesketh, M.J. Savelski, Is process simulation used effectively in ChE courses?, Chemical Engineering Education. 36 (2002).

[7] P.J. Mosterman, M.A.M. Dorlandt, J.O. Campbell, C. Burow, R. Bouw, A.J. Brodersen, J.R. Bourne, Virtual Engineering Laboratories: Design and Experiments, Journal of Engineering Education. 83 (1994) 279–285. doi:10.1002/j.2168-9830.1994.tb01116.x.

[8] S. Joseph, Virtual Laboratories Perspectives from Higher Education Institutes, Digital Learning. (2012) 1–5.

[9] P.C. Wankat, Integrating the use of commercial simulators into lecture courses, Journal of Engineering Education. 91 (2002) 19–23. doi:10.1002/j.2168-9830.2002.tb00668.x.

[10] P.M. Menghal, A.J. Laxmi, Real time simulation: A novel approach in engineering education, 2011 3rd International Conference on Electronics Computer Technology. 1 (2011) 215–219. doi:10.1109/ICECTECH.2011.5941592.

[11] A.R. Kaye, L.H. Salud, Z.B. Domont, K. Blossfield Iannitelli, C.M. Pugh, Expanding the use of simulators as assessment tools: The new pop quiz, in: Studies in Health Technology and Informatics, 2011: pp. 271–273. doi:10.3233/978-1-60750-706-2-271.

[12] C. Koh, H.S. Tan, K.C. Tan, L. Fang, F.M. Fong, D. Kan, S.L. Lye, M.L. Wee, Investigating the Effect of 3D Simulation Based Learning on the Motivation and Performance of Engineering Students, Journal of Engineering Education. 99 (2010) 237–251. doi:10.1002/j.2168-9830.2010.tb01059.x.

[13] S.E. Moll, J.-A. Moraño, L.M. Sánchez-Ruiz, N. Llobregat-Gómez, Orbital Mechanics via a Simulation-based Learning, in: Proceedings of the 3rd International Conference on Technological Ecosystems for Enhancing Multiculturality, 2015: pp. 291–295. doi:10.1145/2808580.2808624.

[14] A. Pederson, J. Woodburn, J. Carrico, Visualization of Astrodynamics and Attitude Concepts for Education, AAS/AIAA Astrodynamics Specialist Conference. 116 (2003) 1–10. http://analyticalgraphics.com/downloads/support/productSupport/literature/pdfs/whitePapers/Paper03-502.pdf (accessed April 16, 2017).

[15] N.P. Bannister, Active Learning in Physics, Astronomy and Engineering with NASA's General Mission Analysis Tool, Journal of Learning and Teaching in Higher Education. 1 (2018) 7–30. doi:10.29311/jlthe.v1i1.2505.

[16] F. Huang, G. Liu, X. Li, W. Shen, Research on reforming the teaching of satellite communications based on STK, World Transactions on Engineering and Technology Education. 11 (2013) 108–112. http://www.wiete.com.au/journals/WTE%26TE/Pages/Vol.11, No.2 (2013)/10-Huang-F.pdf (accessed April 16, 2017).

[17] D.J. Scheeres, Astrodynamics Education: Simulation and Analysis, Proceedings of the International Symposium on Space Technology and Science. 23 (2002).
[18] B.J. Wadsworth, Piaget's theory of cognitive and affective development: Foundations of constructivism, 5th ed., 5th ed., Longman Publishing, White Plains, NY, 1996. doi:http://doi.apa.org/psycinfo/1996-97227-000.
[19] S. Sjøberg, Constructivism and learning, in: International Encyclopedia of Education, 2010. doi:10.1016/B978-0-08-044894-7.00467-X.
[20] K.S. Taber, Beyond constructivism: The progressive research programme into learning science, Studies in Science Education. 42 (2006) 125–184. doi:10.1080/03057260608560222.
[21] A.C. Maskiewicz, J.E. Lineback, Misconceptions are "so yesterday!," CBE Life Sciences Education. 12 (2013) 352–356. doi:10.1187/cbe.13-01-0014.
[22] S. Streicher, K. West, D. Fraser, J. Case, Learning through Simulation: Student Engagement, Chemical Engineering Education. 39 (2005) 288–295. http://www.diva-portal.org/smash/get/diva2:106971/FULLTEXT02.pdf (accessed May 8, 2017).
[23] P. Goodyear, A knowledge-based approach to supporting the use of simulation programs, Computers and Education. 16 (1991) 99–103. doi:10.1016/0360-1315(91)90049-W.
[24] A. Parush, H. Hamm, A. Shtub, Learning histories in simulation-based teaching: The effects on self-learning and transfer, Computers and Education. 39 (2002) 319–332. doi:10.1016/S0360-1315(02)00043-X.
[25] C.H.J. Davies, Student engagement with simulations: A case study, Computers and Education. 39 (2002) 271–282. doi:10.1016/S0360-1315(02)00046-5.
[26] F. Marton, Necessary conditions of learning, Routledge, New York and London, 2014. doi:10.4324/9781315816876.
[27] F. Marton, A.B.M. Tsui, P.P.M. Chik, P.Y. Ko, M.L. Lo, A.B.M. Tsui, P.P.M. Chik, P.Y. Ko, M.L. Lo, Classroom Discourse and the Space of Learning, 1st ed., Routledge, New York, 2004. doi:10.4324/9781410609762.
[28] D. Fraser, R. Pillay, L. Tjatindi, J. Case, Enhancing the learning of fluid mechanics using computer simulations, Journal of Engineering Education. 96 (2007). http://search.proquest.com/openview/abbd2f832222aa8da03ff5115dfa72ed/1?pq-origsite=gscholar&cbl=42405 (accessed April 16, 2017).
[29] G. Åkerlind, From Phenomenography to Variation Theory: A review of the development of the Variation Theory of Learning and implications for pedagogical design in higher, HERDSA Review of Higher Education. 2 (2015). http://www.herdsa.org.au/system/files/HERDSARHE2015v02p05_0.pdf (accessed November 22, 2018).
[30] J.J. Sellers, W.J. Astore, R.B. Giffen, W.J. Larson, D. Kirkpatrick, A. Shute, D. Gay, Understanding space : an introduction to astronautics, 3rd ed., McGraw-Hill Higher Education, New York, 2005.
[31] V. Pisacane, Fundamentals of space systems, 2nd ed., Oxford University Press, Oxford, 2005. https://books.google.co.uk/books?hl=en&lr=&id=uTwb7d8PTXMC&oi=fnd&pg=PR9&ots=EDO0FOroXc&sig=ZKfj1Xhd_qvPN35LbRlZ52LAo3k (accessed June 3, 2019).
[32] P.M. Sadler, H. Coyle, J.L. Miller, N. Cook-Smith, M. Dussault, R.R. Gould, The Astronomy and Space Science Concept Inventory: Development and Validation of Assessment Instruments Aligned with the K–12 National Science Standards, Astronomy Education Review. 8 (2010) 010111–1. doi:10.3847/AER2009024.
[33] D. Fraser, R. Pillay, L. Tjatindi, J. Case, Enhancing the learning of fluid mechanics using computer simulations, Journal of Engineering Education. 96 (2007) 381. doi:10.1002/j.2168-9830.2007.tb00946.x.
[34] M. Jah, S. Hughes, M. Wilkins, T. Kelecy, The General Mission Analysis Tool (GMAT):

A New Resource for Supporting Debris Orbit Determination, Tracking and Analysis, in: Fifth European Conference on Space Debris, 2009: p. Vol 672. http://aero.tamu.edu/sites/default/files/faculty/alfriend/S2.1 Wilkins.pdf (accessed April 16, 2017).
[35] S. Hughes, R. Qureshi, S. Cooley, J.J.K. Parker, T. Grubb, Verification and Validation of the General Mission Analysis Tool (GMAT), in: AIAA/AAS Astrodynamics Specialist Conference, AIAA SPACE, San Diego, CA, 2014: p. 4151. http://arc.aiaa.org/doi/pdf/10.2514/6.2014-4151 (accessed April 16, 2017).
[36] E. Mazur, Education: Farewell, lecture?, Science. 323 (2009) 50–51. doi:10.1126/science.1168927.

APPENDIX A

QUESTIONS (answers in bold).

1. Orbital element measurement
   Which of the following are true?
   a. Argument of perigee is measured from perigee to the true anomaly
   b. Argument of perigee is measured from vernal equinox to the perigee
   c. Argument of perigee is measured from perigee to the ascending node
   d. Argument of perigee is measured from the vernal equinox to the ascending node
   e. None of the above.

2. Orbital element listing
   The Keplerian orbital elements include the following (select one answer):
   a. Semi major axis, inclination, eccentricity, argument of perigee, right ascension of ascending node, mean anomaly
   b. Semi major axis, inclination, eccentricity, argument of perigee, ascending node, true anomaly
   c. Semi major axis, inclination, eccentricity, argument of perigee, right ascension of ascending node, true anomaly
   d. Semi major axis, inclination, eccentricity, argument of perigee, ascending node, mean anomaly

3. Velocities of satellites
   Two satellites are travelling in circular orbits around the Earth. Satellite A is travelling at 3km/s and satellite B is travelling at 7km/s. Which of the following are likely to be true?
   a. A is in GEO, B is in LEO
   b. B is in GEO, A is in LEO
   c. They are both in LEO at different altitudes
   d. They are both in GEO at different inclinations
   e. None of the above

4. Geostationary visualization
   A satellite in geostationary orbit (select all that apply):
   a. Is stationary in space and hovers above the Earth

b. Orbits the Earth
c. Has the same period as the Earth's rotation period
d. Has an inclination of 98 degrees
e. Orbits the Earth at 38000km altitude

5. Ground tracks
Look at the following ground track of a satellite (Figure A1), what explains the distance between each successive pass of the satellite? (select all that apply)
a. The argument of perigee is changing as the satellite orbits the Earth
b. The inclination is changing as the satellite orbits the Earth
c. The Earth is rotating under the satellite
d. The right ascension of the ascending node causes the ascending node to move with each orbit

Figure A1: the ground track of a satellite

6. Ground track inclination
Which piece of information can we deduce from the ground track?
a. Semi major axis
b. Eccentricity
c. Inclination
d. Argument of perigee

7. Hohmann number of burns
A Hohmann transfer consists of (select one):
a. A burn from a circular orbit to a transfer orbit
b. A burn from an elliptical orbit to a transfer orbit
c. A burn to escape velocity
d. A burn from a circular to a transfer orbit, then a burn to circularise

8. Rendezvous
For a Soyuz to catch up with a space station 500km ahead of it in the same circular orbit over the period of several orbits, the Soyuz needs to (select one):
a. Accelerate with prograde burns
b. Decelerate with retrograde burns and then accelerate with prograde burns
c. Accelerate manually with small prograde burns
d. Accelerate with prograde burns and then decelerate with retrograde burns